# Spectrum and Propagation Measurements

The radio spectrum is an enigmatic natural resource that offers immense benefit to industry, government, and private citizens by supporting radio/wireless communications and a wide variety of other systems such as radar and remote sensing. It is non-depleting and exists everywhere, but it is finite and can be rendered less useful by noise and interference. Until recently, traditional methods of allocating spectrum and assigning channels have ensured effective and efficient use of the spectrum. Today, the rapidly expanding competition for spectrum use and the plethora of new signal types and applications have created an apparent shortage of radio spectrum. While new spectrum management methods will alleviate this problem, they cannot do so without increasingly more complex knowledge of the existing signals and noise environment and better understanding of how systems that share spectrum affect each other.

The Spectrum and Propagation Measurements Division provides the technical information needed to enable more effective and efficient use of the spectrum, thus enabling spectrum allocation and sharing regulations and policies that are effective, reliable, and enduring. To do so, the Division performs analyses and measurements of the effects of radio signals on the spectrum and on other systems. Measurements and assessments of spectrum occupancy can be accomplished at any location using the mobile Radio Spectrum Measurement Science system. New measurement methods are developed and complex testing is accomplished in well-equipped laboratories and at the Table Mountain Field Site.

The following areas of emphasis are indicative of the work done in the Division recently in support of NTIA, other Federal Agencies, academia, and private industry.

## Areas of Emphasis

**Radio Spectrum Measurement Science (RSMS) Operations**
The Institute's RSMS is comprised of laboratory, transportable, and mobile facilities. This capability is used to assess spectrum occupancy and usage, and electromagnetic compatibility, and to resolve interference problems. This project is funded by NTIA.

**RSMS 4th Generation System Development**
The Institute continually refines and develops measurement methods, both established and new, supported by hardware and software. The RSMS fourth generation system software is capable of fully autonomous operation and remote monitoring, uniform data recording and storage, and powerful analysis and display routines. This project is funded by NTIA.

**Table Mountain Research Program**
The Institute's field site, protected by state law and Federal Regulation as a radio quiet zone, is used by many operations and experiments that require protection from strong, external radio signals, and minimum vibration. Research into new spectrum occupancy measurement methods, including radio noise measurement, new antennas, and complex radar measurements, are conducted by ITS at the site. These projects are funded by NTIA.

**Spectrum Efficiency Research and Engineering**
The Institute pursues investigations of the efficient and effective use of the radio spectrum, including allocation and assignment methods. Definitions for spectrum efficiency and effectiveness can be nontrivial and elusive. The Institute compares actual measurements of band and channel usage with known assignments to determine the merits of new and competing channel assignment schemes. This project is funded by NTIA.

**Signal Characteristics, Spectral Emissions, and Interference Analyses**
The Institute largely completed a complex assessment of the interference potential of ultrawideband (UWB) signals in FY 2006. This study required the utmost care and thoroughness to determine which characteristics of a variety of UWB signals were best correlated with interference effects observed in a digital television satellite receiver. This project is funded by Freescale, Inc.

# Radio Spectrum Measurement Science (RSMS) Operations

### Outputs

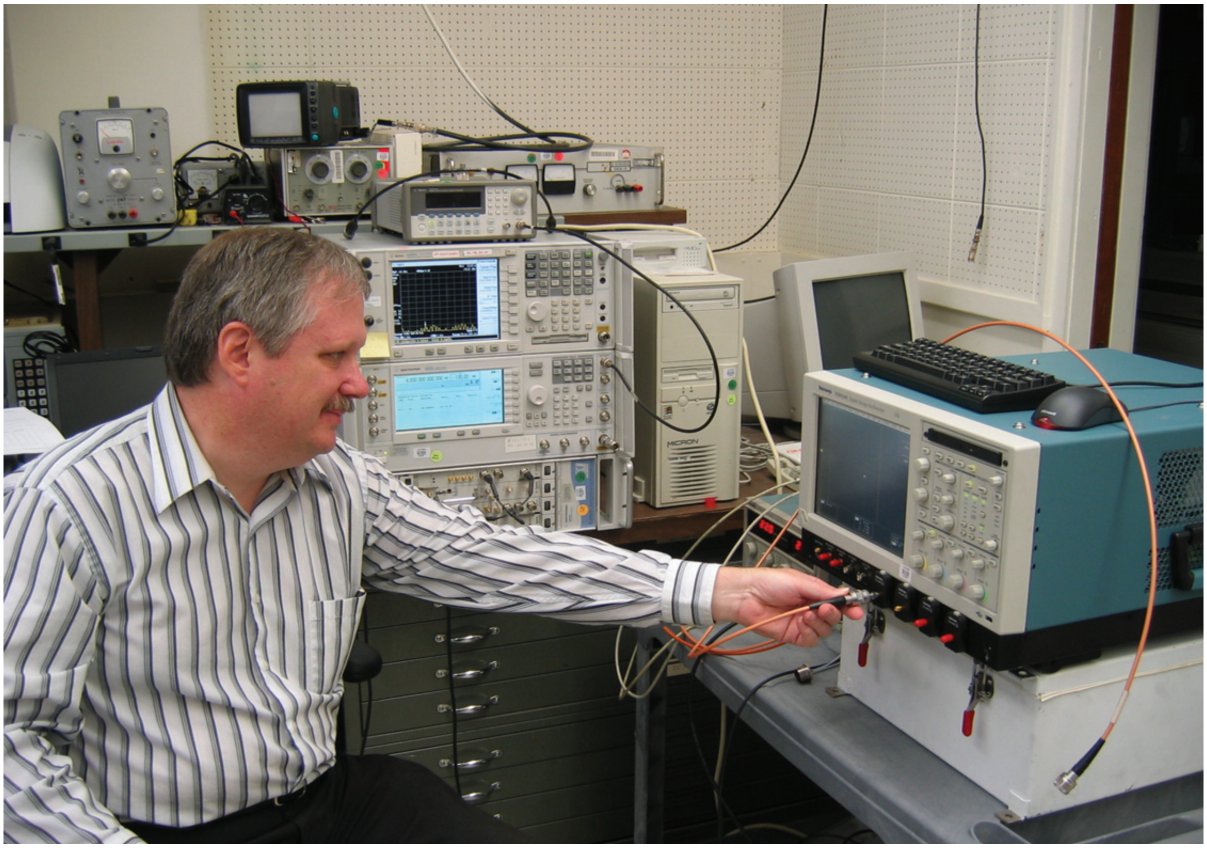
- Measurements to determine compatibility between prototype 5-GHz dynamic frequency selection (DFS) devices and a 5-GHz radar.
- Measurements and draft report on land mobile radio (LMR) channel occupancy in Federal bands 162-174 MHz and 406-420 MHz.
- Measurements to address compatibility between radiolocation and maritime and aeronautical services in the bands 9000-9200 MHz and 9300-9500 MHz.

The Radio Spectrum Measurement Science (RSMS) group is given the task of performing critically needed radio signal measurements necessary for making decisions regarding Federal Government spectrum allocations. As stated under Departmental Organization Order 25-7, issued 5 October 1992, and amended December 1993, the NTIA Office of Spectrum Management (OSM) is responsible for identifying and making arrangements for measurements necessary to provide NTIA and the various departments and agencies with information to ensure effective and efficient use of the spectrum. RSMS resides at ITS in Boulder, Colorado, and is tasked to perform measurements in support of OSM as required to fulfill their mission. ITS, through the RSMS Operations project, provides OSM and the executive branch with critically needed radio spectrum data, data analysis, reports, and summaries. The four basic areas of RSMS are 1) spectrum surveys and channel usage, 2) equipment characteristics and compliance, 3) interference resolution and compatibility, and 4) signal coverage and quality. In FY 2006, several different measurements were performed in support of the basic mission.

Dynamic frequency selection (DFS) is a method whereby a radio local area network (RLAN) device, using the 5-GHz band for unlicensed operations, will detect the operations of radar and promptly evacuate the channel if the radar is present. In FY 2004-2005, ITS performed testing to demonstrate DFS proof of concept with a table of radar signals developed in conjunction with the FCC, industry, the Department of Defense, and NTIA. In December 2005, field measurements were conducted to determine compatibility between prototype 5-GHz DFS devices and a 5-GHz radar at a missile facility in New Mexico. In preparation for these measurements, aggregate radiated emissions of multiple DFS devices were recorded at the Table Mountain facility located north of Boulder, Colorado, for the purpose of modeling these signals. ITS also provided assistance to Compliance Certifications Services, the Federal Communications Commission (FCC), and OSM with regard to simulated pulsed signals used for DFS compliance testing. The test results will help determine whether this technology is able to move forward toward deployment in commercially available RLAN-type communication devices.

In the early part of FY 2006, measurements were conducted in the Denver area to measure and provide a report on land mobile radio (LMR) channel occupancy in Federal bands 162-174 MHz and 406-420 MHz. These measurements supplement earlier LMR measurements in Washington, DC, for which a report is currently under review by OSM and the Interdepartment Radio Advisory Committee (IRAC). These measurements are part of NTIA's effort to improve the spectrum efficiency of Federal radio usage. Specifically, this effort was undertaken to help obtain data required to realistically design future possible shared trunked systems for Federal radio users and determine long-term usage trends by comparing results with previous measurements taken in the same location in 1986 and 1989. The measurements were made using new equipment and techniques developed at ITS that measure large areas of the spectrum and process it to obtain simultaneous signal levels of up to 480 individual LMR channels. These techniques provided faster measurements, but also allowed enhanced post-processing of the data to remove measurement defects.

In support of an International Telecommunication Union — Radiocommunication Sector (ITU-R) World Radiocommunication Conference (WRC-07) agenda item to upgrade the status of the radiolocation service in the bands 9000-9200 MHz and 9300-9500 MHz to primary status, three additional measurements were conducted in FY 2006: on a precision approach radar, an airborne weather radar, and an ASDE-X radar. The measurements were designed



*An ITS engineer conducting pulsed waveform measurements in the ITS laboratory (photograph by J.R. Hoffman).*

to address compatibility between radiolocation and maritime and aeronautical services in the above mentioned bands. Waveforms of the radiolocation systems were generated and injected into the receivers of the three radionavigation systems to determine levels of degradation.

To investigate waiver applications to the FCC's ultrawideband Part 15 Rules permitting devices to employ swept frequency techniques, additional measurements using different averaging times were conducted at the ITS Boulder Labs. The purpose was to provide an understanding of swept signals at the output of various filter bandwidths and to provide information to develop test procedures that could be used in compliance measurements.

Point-to-point microwave link measurements were conducted in the spring of FY 2006 to search for and record the signals from various links in the 7.125-8.8 GHz bands. These measurements were conducted as part of NTIA's effort to improve the spectrum efficiency of Federal radio usage. Specifically, this effort was undertaken to explore various techniques and capabilities for performing future, more extensive Fixed Services measurements in order to determine band usage.

Multiple measurements of various simulated chirped pulse waveforms and frequency modulated continuous waveforms were conducted in the ITS laboratory during the latter part of FY 2006. The purpose of these measurements is to provide measured waveforms to compare the 20- and 40-dB bandwidths for proposed equations used to calculate the bandwidths.

In support of an ongoing effort to characterize various radar emissions, measurements were conducted on three separate radars in the Baltimore, Maryland, area during the spring of FY 2006. This was in support of work with the ITU-R JRG 1A/1C/8B to develop ITU radar emission limits, which the committee has been tasked to review.

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# RSMS 4th Generation System Development

### Outputs

- Enhancements of existing preselectors.
- Real-time fully automated direction-finding system that can be used with pulsed signals such as radar.
- Several new ITS custom-designed software modules for instrument control and measurement.

The 4th generation system for Radio Spectrum Measurement Science (RSMS) consists of state-of-the-art tools (vehicle, software, and hardware) necessary for making measurements to characterize spectrum occupancy, ensure equipment compliance, determine electromagnetic compatibility, and analyze interference problems. The development of the 4th generation system originated out of the recognized need to upgrade to the latest technology for RSMS operations. RSMS operations, in turn, directly supports NTIA by providing critical measurement support for determining policies affecting both the public and private sectors. To this end, several new capabilities and improvements have been added to the system in FY 2006.

Integral to the RSMS measurement system has been the development of customized preselector units that filter out unwanted signals and amplify the input to increase system sensitivity. Over the last few years, two new fully functional 4th generation preselectors have been designed and constructed — one for frequencies between 0.5–18.0 GHz and the other for frequencies between 18.0–26.5 GHz. Both preselectors are protected against strong signals by highly shielded enclosures and are controlled via fiberoptic connections to prevent signals coupling into control lines. In addition to these 4th generations units, several improvements to the existing preselectors have been made. In FY 2006, testing, repair, and improvements to the 3rd generation preselectors, as well as development of control software, has made it possible to integrate these older, but still very functional, devices into the 4th generation system. In addition, several improvements have been made to existing tunable yttrium-iron-garnet (YIG) filter systems frequently used for radar measurement. A YIG tracking system is currently under development for the purpose of tracking frequency sweeps of spectrum analyzers, and a YIG calibration software routine has been developed that allows periodic characterization of the filter for offset control. Under the development of the 4th generation software, computer automated control of each of the units — new and old — has been integrated into the larger software package. Modularized instrument software units have made it possible to seamlessly swap out preselector units for different applications of the same measurement capabilities.

Currently in progress is the development of real-time "signal direction finding" capabilities. ITS engineering staff have been working together to develop these capabilities through implementation of digital control and processing using Field Programmable Gate Array (FPGA) technology. The system switches through the different antennas of a six-sided array to determine the angle of signal arrival. Using rapid digital processing and a switch control by the FPGA, information is relayed via the Internet to a computer, which can then be used for real-time high-gain antenna positioning toward stationary or moving targets. One of the advantages of this system over most off-the-shelf systems is that it can be used with pulsed signals such as radar. Because it is implemented in software as an instrument module, this system is easily integrated into the larger RSMS software package for use with a variety of measurement capabilities. Development of this system using FPGA technology will not only provide signal direction-finding capabilities but will open up a whole new way of acquiring and processing data, using what is essentially a hardware re-programmable instrument that can be used for many different applications.

Two recent additions to the RSMS software have been the development of a rotator instrument control and an azimuth signal search routine. The rotator instrument control is a software module that can be integrated into the larger RSMS software, allowing remote control of an antenna position device. The signal search routine uses the rotator control software in combination with a spectrum analyzer to perform an azimuth sweep at a single frequency


*RSMS 4th generation vehicle parked at the ITS Boulder Laboratories (photograph by J.R. Hoffman).*

to determine the angle of greatest signal power. This routine is used to find signals on the horizon to determine the best azimuth angle setting for pointing narrow beam antennas. It can also be used to characterize antenna patterns.

Several additions have also been made to RSMS software measurement routines. These include an automated "swept measurement," a "swept calibration" routine, a "stepped calibration" routine, and a "spectrum analyzer data dump." The "swept measurement" is a routine that automates the acquisition of spectrum traces from multiple bands and stores data in a format that is easily usable. The "swept calibration" routine performs an automated system calibration where the measurement utilizes an externally tuned YIG or fixed filters. The "stepped calibration" routine performs an automated system calibration where YIG tuning is performed strictly through software control. The "spectrum analyzer data dump" routine provides quick setup of the RF path and downloads spectrum analyzer traces referenced to different locations along the RF path.

New features expected in FY 2007 include enhanced data file management, a vector signal analyzer instrument control module, a point-to-point microwave measurement system and software, a new noise measurement routine, a scheduler for automated control of multiple measurements, the completion of the YIG tracking system, and the development of an RSMS-4 low frequency preselector.

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# Table Mountain Research Program

## Outputs

- Tests of a prototype 3-axis antenna designed to study the total incident field and polarization of a radiated signal.
- New NOAA Weather Radio testing laboratory.
- Upgrades to the turntable facility at the Table Mountain field site to improve capability for testing the performance of antenna systems mounted on vehicles.
- Simulations of complex signals such as UWB, DTV, and man-made noise.

The Table Mountain Field Site and Radio Quiet Zone supports fundamental research into the nature, interaction, and evaluation of telecommunication devices, systems, and services. To achieve this goal, the Table Mountain Research Project actively solicits research proposals from inside the Institute as well as from external agencies.

The results of this work are disseminated to the public via reports, technical papers, journal articles, conference papers, web documents, and computer programs. Activities this year have included:

**Digital Television Project:**
NTIA has been tasked with the development of a program for the distribution of digital to analog converter boxes to facilitate the transition to digital television (DTV) broadcast scheduled to take place on February 17, 2009. To support this program, a system capable of generating DTV signals was assembled, allowing ITS to study the characteristics of the signals in a controlled environment. Additionally, a study to identify DTV performance metrics and to develop the procedures needed to evaluate the performance of DTV converter boxes was initiated.

*Testing the pattern of antennas mounted on a mock-up of an unmanned aerial vehicle (UAV) at the Table Mountain field site, part of the cooperative research and development agreement (CRADA) between ITS and Johnson's Jobs (photograph courtesy of Russ Johnson, Johnson's Jobs).*

*Set-up for testing of 3-axis antenna at Table Mountain field site (photograph by R.N. Statz).*

**NOAA Weather Radio Testing:**
To help ensure that radios displaying the NOAA Weather Radio emblem meet the NOAA performance criteria, ITS established a laboratory at the Table Mountain field site to measure the performance of these radios. This leverages earlier work undertaken in FY 2004 where ITS examined the overall performance of the NOAA Weather Radio system from signal generation to signal reception. This test facility provides NOAA with performance data based on tests outlined by the Consumer Electronics Association standard CEA-2009.

**FY 2006 Cooperative Research and Development Partners**

- Eton Corporation
- Johnson's Jobs
- RF Metrics Corporation
- Lockheed Martin/Coherent Technologies
- Deep Space Exploration Society
- University of Colorado, Ad Hoc UAV Ground Network (AUGNet)

## Recent Publications


J. Diverdi, "Simple mapping project (SMP) Interim Report," Deep Space Exploration Society, Jun. 2006.

F. Sanders, J. Wepman, and S. Engelking, "Development of performance testing methods for dynamic frequency selection (DFS) 5-GHz wireless access systems (WAS)," in "Proceedings of the International Symposium on Advanced Radio Technologies: March 7-9, 2006," P. Raush and K. Novik, Eds., NTIA Special Publication SP-06-438, Mar. 2006, pp. 39-48.

D. Henkel and T.X. Brown, "On controlled node mobility in delay-tolerant networks of unmanned aerial vehicles," in "Proceedings of the International Symposium on Advanced Radio Technologies: March 7-9, 2006," P. Raush and K. Novik, Eds., NTIA Special Publication SP-06-438, Mar. 2006, pp. 29-38.

R. Howe, "Detection of gamma ray bursts and X-ray transient SGR 1806-20 with VLF radio telescopes," *Open European Journal on Variable Stars*, ISSN: 1801-5964, OEJV# 0022, Feb. 2006.

F. Sanders and B. Ramsey, "Phased array antenna pattern variation with frequency and implications for radar spectrum measurements," NTIA Technical Report TR-06-436, Dec. 2005.

F. Sanders and B. Ramsey, "Comparison of radar spectra on varying azimuths relative to the base of the antenna rotary joint," NTIA Technical Memorandum TM-05-430, Aug. 2005.

T. Brown, S. Doshi, S. Jdhav, D. Henkel, and R. Thekkekunnel, "A full scale wireless ad hoc network test bed," in "Proceedings of the International Symposium on Advanced Radio Technologies: March 1-3, 2005," J.W. Allen and J. Ratzloff, Eds., NTIA Special Publication SP-05-418, Mar. 2005, pp. 51-60.

J.W. Allen, "Gain characterization of the RF measurement path," NTIA Report TR-04-410, Feb. 2004.

J.W. Allen and T. Mullen, "Digital television (DTV) field strength and video quality study," NTIA Technical Memorandum TM-03-405, Aug. 2003.



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# Spectrum Efficiency Research and Engineering

## Outputs

- Consultation with OSM and internal papers on spectrum efficiency planning.
- Consultation with OPAD and internal papers on flexible-use spectrum rights.

NTIA is pursuing an extensive multi-pronged program to improve the spectrum efficiency (SE) of Federal radio systems. This program was given additional importance by the May 2003 announcement of a Presidential Spectrum Policy Initiative to promote the development and implementation of a U.S. spectrum management policy for the 21st century. Although most of this work will be accomplished by NTIA in Washington, ITS is developing theoretical concepts and practical applications for improved SE.

NTIA's Office of Spectrum Management (OSM) asked ITS to examine possible metrics that describe the SE of several types of radio services. Previous work concentrated on land mobile radio (LMR) systems. The first phase of this work has been completed (see Hoffman et al. 2006 in "Recent Publications" below). A "signal capacity" model was developed to provide a combined geographical coverage "footprint" of the multiple independent existing radio systems now serving Federal Agencies, based on license data from the Government Master File. This model showed that 268 separate LMR radio channels were available in downtown Washington, DC, as well as summarizing the coverage of Federal LMR systems within a 100-mile radius.

The second phase of this work was the measurement of LMR traffic (Erlangs) in the Washington, DC, area, using the ITS RSMS-4 system, as described on pp. 6-7. The data from these first two phases can be used to design possible future alternative shared LMR systems, since they provide information on the number of channels available at each location, as well as the average traffic carried by each channel.

More recently, ITS work has shifted towards SE models of Fixed Services (FS) systems, including point-to-point microwave systems. Two distinct types of services are provided by FS radios: transport and access services. Transport services are provided where the base station relays all of the data it receives to the next station, without originating or terminating any data locally. Transport stations are often arranged in long chains where data is passed from station to station, sometimes transporting data for hundreds of miles. An "access" station uses or generates data locally or provides wireless connections to wired broadband networks. Some stations provide a mix of access and transport services.

Since one of the measures of SE calculation is to compare a given system with a theoretical maximum-performance system, it is useful to consider how to build such a system — even if many approximations need to be made. Figure 1 shows one possible maximum-traffic transport system.

Figure 1a shows a single link in a chain of FS transport stations, with data being transmitted from station $X_1$ to station $X_2$. The single link would be designed to carry a maximum amount of data between $X_1$ and $X_2$.

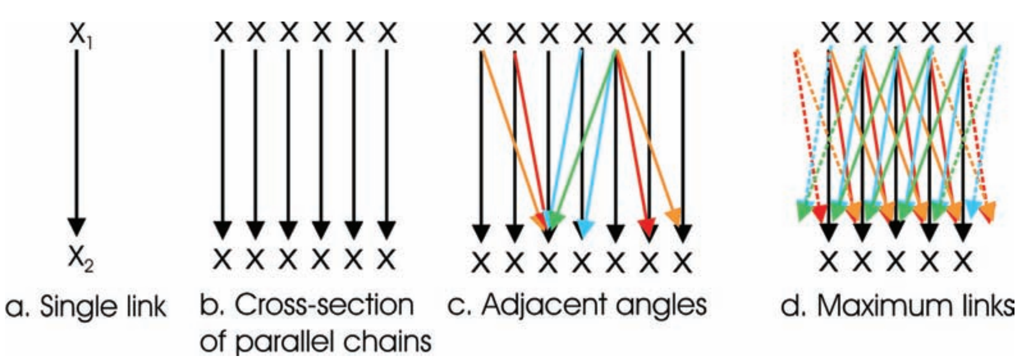


*Figure 1. Maximum service transport system examples.*

Figure 1b shows the configuration of a set of corresponding links in a set of parallel chains, where the transport capacity per unit of total path width is dependent on how closely the parallel chains can be spaced. All sites from the corresponding link of a chain use the same frequency sets, using the narrow antenna beamwidth to prevent interference from nodes on the adjacent microwave chains.

Figure 1c shows that a transport system could also support transport links to and from corresponding antennas on the adjacent parallel chains of microwave licenses, using the narrowness of the antenna's beamwidth to select the desired signal.

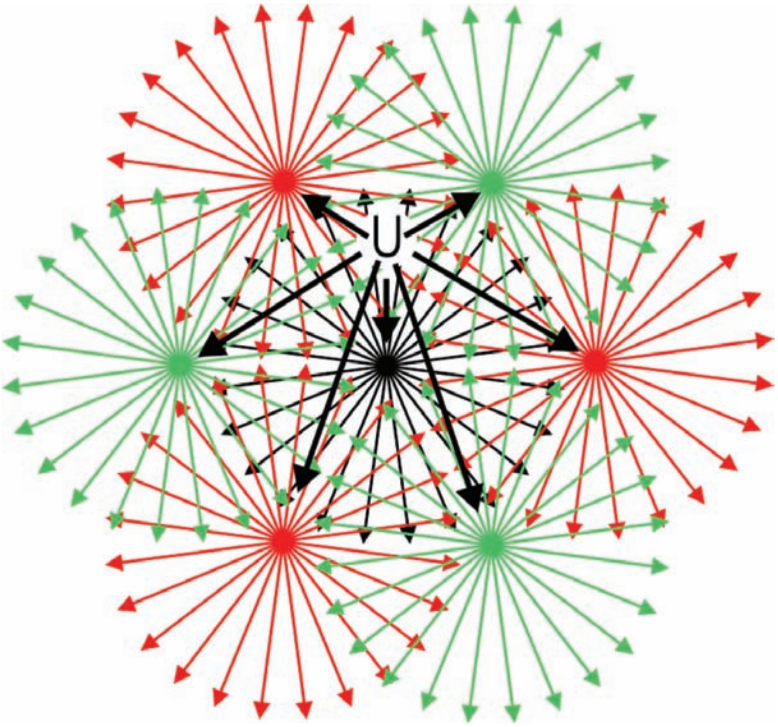

*Figure 2. Maximum service access system example.*

Figure 1d shows a possible arrangement of antenna beams that exploit "in-line" and "1st-adjacent-chain" paths. Figure 1d could be expanded to include "nth-adjacent-chain paths." This model probably represents something close to a real-world maximum-traffic transport system. In the real world, however, optical fiber would probably be installed long before such dense microwave networks would be built.

Similar models have been considered for the maximum access capacity of FS radios. Figure 2 shows a possible FS maximum access configuration, with a user "U" surrounded by various access sites with multiple directional antennas. The benefit from access services is merely the total number of bits transmitted across all paths. Total service can be maximized by decreasing the average path length (moving access nodes closer to users for better spatial frequency reuse) and decreasing antenna beamwidth (allowing better angular frequency reuse).

ITS has also been working with NTIA's Office of Policy Analysis and Development (OPAD) on various spectrum sharing strategies, including flexible-use spectrum rights. Flexible-use rules would be useful where spectrum is available for some services but not for others. Flexible-use rules allow changes in the way spectrum is used, including the use of secondary markets to rapidly acquire suitable spectrum. However, a switch to flexible-use rights requires individual users to have more system design expertise than is required when deploying "cookie-cutter" standardized systems licensed in most of the existing command-and-control frequency bands. Flexible-use issues involve: 1) an unambiguous description of the spectrum space (electrospace) that is licensed, 2) a minimal set of rules/property rights that allow the design of new radio systems while minimizing interference, and 3) a set of procedures for licensing systems and determining responsibility for any interference.

**Recent Publications**

R. J. Matheson, "Principles of flexible-use spectrum rights," *Journal of Communications and Networks*, vol. 8, no. 2, pp. 144-150, Jun. 2006.

C. Hoffman, R. Matheson, F. Najmy, and R. Wilson; "Federal land mobile operations in the 162-174 MHz band in the Washington, D.C., area, Phase 1: Study of agency operations," NTIA Report 06-440, Aug. 2006.

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# Signal Characteristics, Spectral Emissions, and Interference Analyses

### Outputs

- Technical publications and presentations demonstrating research results.
- Measurement and analysis of DTV susceptibility to ultrawideband signals.

Since the FCC permitted low power ultrawideband (UWB) emissions between 3.1 and 10.6 GHz in February 2003, a number of companies have developed new UWB technologies for application in wireless personal area networking (WPAN) to achieve high data rates at short distances (nominally less than 10 meters). Examples of these developments include Multi-band Orthogonal Frequency-Domain Multiplexing (MB-OFDM) and Direct-Sequence Ultrawideband (DS-UWB) technologies. MB-OFDM achieves its ultra-wide bandwidth with a 528-MHz wide OFDM signal that hops between 14 different bands. In contrast, DS-UWB combines conventional spread spectrum techniques and pulse shaping to achieve its ultra-wide bandwidth. Questions arose regarding how UWB signals interfere with legacy systems such as C-band satellite television, which demodulates signals that lie within the frequency band allocated for UWB operations. On March 22, 2004, ITS entered into a Cooperative Research and Development Agreement (CRADA) with Freescale Inc. to address these questions.

ITS researchers hypothesized that UWB interference potential could be quantified in terms of UWB signal characteristics. To test this hypothesis, a test system was designed and built to inject UWB signals with known characteristics into a C-band satellite digital television (DTV) receiver and quantitatively measure interference susceptibility via signal quality metrics, e.g., segment error rate, pre-Viterbi bit error rate, and modulation error ratio, taken from various

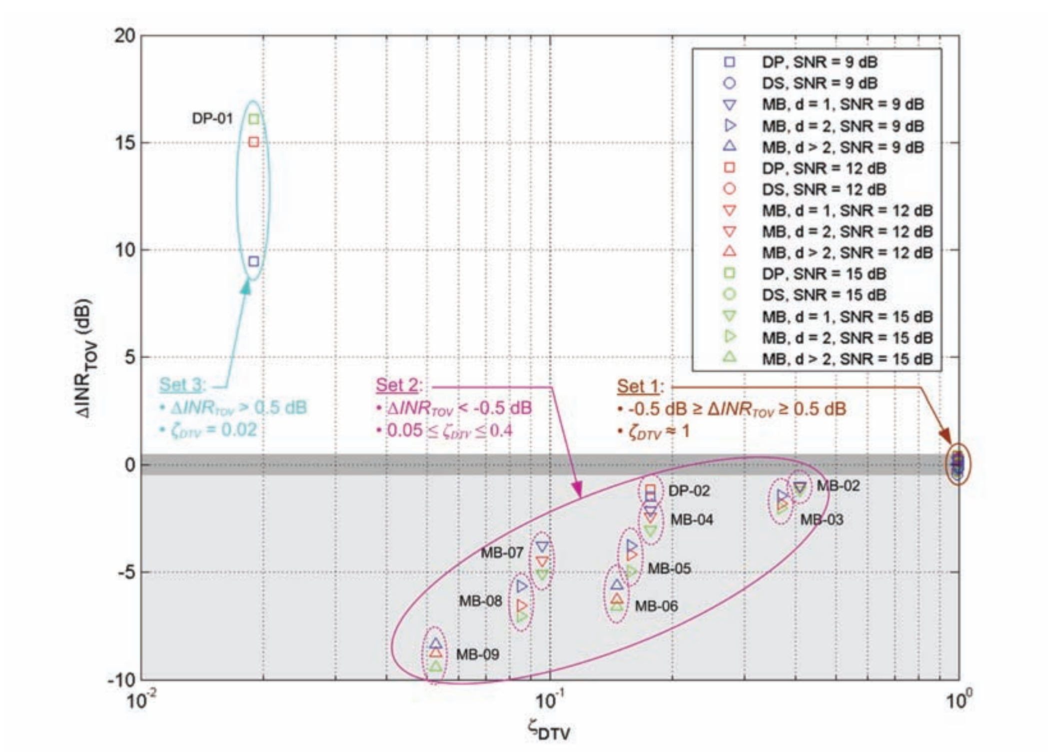


*Figure 1. DTV susceptibility vs. fractional on-time of UWB interference signals in the bandwidth of the victim receiver. Contours are drawn around signals that caused similar interference effects to the DTV receiver.*

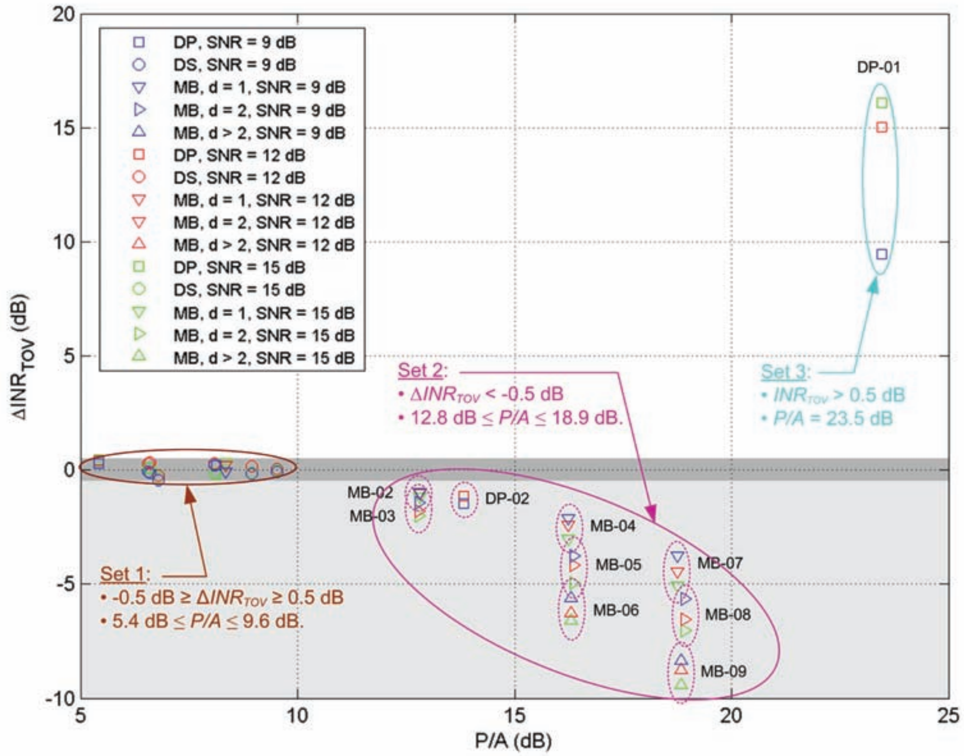


*Figure 2. DTV susceptibility versus peak-to-average ratio of UWB interference signals in the bandwidth of the victim receiver. Contours are drawn around signals the caused similar interference effects to the DTV receiver.*

points in the receiver signal processing chain. Results from the experiment were published in a three-part NTIA Report series entitled "Interference Potential of Ultrawideband Signals." Part 1 describes the test setup and procedures in detail. Part 2 provides signal characterization and DTV susceptibility results for gated-noise interference. Finally, Part 3 provides characterization and DTV susceptibility results for UWB interference. It was found that categorization of the UWB signals into three signal sets of common DTV susceptibility could be achieved with *a priori* knowledge of the interference signal characteristics and bandwidth of the victim receiver. These sets are illustrated in Figures 1 and 2, which plot DTV susceptibility versus fractional on-time ($\zeta_{DTV}$) and peak-to-average ratio ($P/A$), respectively. DTV susceptibility was quantified by the metric $\Delta INR_{TOV}$, which is the interference-to-noise ratio at the threshold of visibility normalized to the Gaussian noise interference case.

**Recent Publications**


M. Cotton, R. Achatz, J. Wepman, B. Bedford, "Ultrawideband interference potential: Part 1 – Procedures to characterize ultrawideband emissions and characterize interference susceptibility of C-band satellite digital television receivers," NTIA Report TR-05-419, Feb. 2005.

M. Cotton, R. Achatz, J. Wepman, P. Runkle, "Ultrawideband interference potential: Part 2 – Measurement of gated-noise interference to C-band satellite digital television receivers," NTIA Report TR-05-429, Aug. 2005.

M. Cotton, R. Achatz, J. Wepman, R. Dalke, "Ultrawideband interference potential: Part 3 – Measurement of ultrawideband interference to C-band satellite digital television receivers," NTIA Report TR-06-437, Feb. 2006.



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